

## Soret and Dufour Effects on Unsteady MHD Flow of a Micropolar Fluid in the Presence of Thermophoresis Deposition Particle

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**Abstract:** In this paper, the unsteady magnetohydrodynamics (MHD) free convection flow of an incompressible and electrically conducting fluid over a stretching surface under the influence of Soret and Dufour effects with thermophoresis has been investigated. The governing equations are solved numerically by using implicit finite-difference scheme. The results of skin friction, the Nusselt number and the Sherwood number are obtained and discussed graphically for various parameters.

**Key words:** MHD • Micropolar fluid • Thermophoresis • Soret and Dufour effects

### INTRODUCTION

The theory of micropolar fluids which was originally formulated by Eringen [1] has been an active area of research for several decades. The micropolar fluids are non-Newtonian fluids consisting of dumb-bell molecules, body fluids colloidal fluids, suspensions fluids, etc. In the theory of micropolar fluid, the local effect arising from the microstructure and the intrinsic motion of fluids elements are taken into account. More detail of this theory and its applications can be found in Ariman *et al.* [2, 3] and books by Lukaszewicz [4] and Eringen [5].

Thermophoresis is a mechanism of migration of small particles in terms of reducing the thermal gradient [6]. It is an effective method for collection of particle [7]. Thermophoresis has got outstanding important in the vast number of application in deposition of silicon thin films, radioactive particles deposition in nuclear reactors, particles impacting the blade surface of gas turbines and aerosol technology. More detail of practical applications of thermophoresis can be found in [8, 9]. Goren [10] was first to analyze the thermophoresis in laminar flow over a flat plate for cold and hot plate conditions. Epstein *et al.* [11] have investigated the effect of the thermophoresis in natural convection flow over a vertical plate. Garg and Jayaraj [12] have investigated the thermophoresis particle deposition in laminar flow over inclined plates. Chamkha and Pop [13] analyzed the natural convection over a vertical flat plate in a porous

medium with thermophoresis. Seddeek [14] numerically studied the effects of variable viscosity and thermophoresis on a boundary layer flow with chemical reaction. Partha [15] analyzed the effects of Soret and Dufour with thermophoresis in a non-Darcy porous medium in the presence of suction/injection.

The Soret and Dufour effects and thermophoresis are very important when the temperature and concentration gradients are high. The thermal-diffusion or Soret effect corresponds to species differentiation developing in an initial homogeneous mixture submitted to a thermal gradient and the diffusion-thermo or Dufour effect corresponds to the heat flux produced by a concentration gradient. Partha [16] has studied the effects of thermal-diffusion and diffusion-thermo in a non-Darcy porous medium with thermophoresis particle deposition. Puvi Arasu *et al.* [17] have analyzed free convective flow with the Soret and Dufour effects over a stretching surface with variable stream conditions with thermophoresis. Recently, Kandasamy *et al.* [18] investigated free convective heat and mass transfer with thermophoresis particle deposition and chemical reaction over a stretching surface with heat source/sink in the presence of Soret and Dufour effects.

The study of magnetohydrodynamics (MHD) of electrically conducting fluid in a micropolar is encountered in many problems in geophysics, astrophysics as well as in engineering applications such as MHD generators, plasma studies, nuclear reactors and

geothermal energy extractions. Hayat and Qasim [19] studied heat and mass transfer on unsteady MHD flow in a micropolar fluid with thermal radiation. Bhuvaneswari *et al.* [20] investigated the effects of heat generation and radiation on heat and mass transfer of a viscous electrically conducting incompressible fluid over a semi-infinite plate in a porous medium. Hayat and Qasim [21] analyzed the effect of thermophoresis on MHD flow with Maxwell fluid with thermal radiation and Joule heating. Recently, Ashraf and Shahzad [22] investigated numerically the effect of radiation on MHD two dimensional boundary layer stagnation-point flows towards the heating shrinking sheet.

The aim of the present research is to study the free convective heat and mass transfer over an unsteady stretching surface in a micropolar fluid in the presence of Soret and Dufour effects with thermophoresis particle deposition. In this study we consider both strong concentrations ( $n=0$ ) and weak concentrations ( $n=1/2$ ). The results obtained under special cases are then compared with previous published results and are found to be in good agreement.

**Mathematical Formulation:** Consider the unsteady MHD free convection flow of an incompressible fluid over a vertical stretching surface in a micropolar fluid with thermophoresis particle deposition. A transverse magnetic field  $B_0$  is imposed along the y-axis. The induced magnetic field is neglected by assuming a very small magnetic Reynolds number. The applied magnetic field is also taken as being weak so that Hall and ion slip effects may be neglected. The stretching surface has linear velocity  $u_w$ . Two equal and opposite forces are introduced along the x-axis so that sheet is stretched with a speed proportional to the distance from the fixed origin  $x=0$ . We assume that the Dufour effect may be described by a second-order concentration derivative with respect to the transverse coordinate in the energy equation whereas Soret effect is described by the second-order temperature derivative in the mass-diffusion equation. Under the usual boundary layer approximation, along with Boussinesq approximations the governing equations are governed by the following equations:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} &= \left( v + \frac{k_1^*}{\rho} \right) \frac{\partial^2 u}{\partial y^2} + \frac{k_1^*}{\rho} \frac{\partial N}{\partial y} \\ - \frac{\sigma B_0^2}{\rho} u &+ g \beta (T - T_\infty) + g \beta^* (C - C_\infty) \end{aligned} \quad (2)$$

$$\rho j \left( \frac{\partial N}{\partial t} + u \frac{\partial N}{\partial x} + v \frac{\partial N}{\partial y} \right) = \gamma \frac{\partial^2 N}{\partial y^2} - k_1^* \left( 2N + \frac{\partial u}{\partial y} \right) \quad (3)$$

$$\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} = \frac{\kappa}{\rho c_p} \frac{\partial^2 T}{\partial y^2} + \frac{D_m \kappa_t}{c_s c_p} \frac{\partial^2 C}{\partial y^2} \quad (4)$$

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = D \frac{\partial^2 C}{\partial y^2} - \frac{\partial (V_T C)}{\partial y} + \frac{D_m \kappa_t}{T_m} \frac{\partial^2 T}{\partial y^2} \quad (5)$$

In above equations  $u$  and  $v$  are the velocity components along the  $x$ - and  $y$ -direction, respectively,  $\beta$  and  $\beta^*$  are the coefficients of thermal and concentration expansions,  $v$  is the specific heat at constant pressure,  $\sigma$  is the kinematic viscosity,  $\rho$  is the electrical conductivity of the fluid,  $D$  is the density of the fluid,  $k$  is the molecular diffusivity,  $N$  is the coefficient of thermal expansion,  $\gamma$  is the components of microrotation or angular velocity whose rotation is in the direction of the  $x,y$ - planes and  $j$  is the microinertia per unit mass,  $\gamma$  is the spin gradient viscosity and  $k_1^*$  is the vortex viscosity, respectively. As it was shown by Ahmadi [23], the spin gradient viscosity  $\gamma$  can be defined as

$$\gamma = \left( \mu + \frac{k_1^*}{2} \right) j = \mu (1 + K/2) j \quad (6)$$

Where  $\mu$  is the dynamic viscosity,  $K = k_1^* / \mu (\mu > 0)$  is the material parameter. We take  $j = v/a$  as a reference length [24]. Equation (6) is invoked to predict the right behavior when the microstructure effects become negligible and the total spin  $N$  reduces to the angular velocity [23, 25]. It should be noted that  $n$  is a constant such that  $0 \leq n \leq 1$ . The case  $n=1/2$  present a strong concentration, which indicates that  $N=0$  near the wall, represents concentrated particle flows in which the micro-elements close to the wall surface are unable to rotate [26]. The case  $n = 1/2$  present the vanishing of the anti-symmetric part of the stress tensor and denotes weak concentrations whereas  $n=1$  is used for modeling of turbulent boundary layer flows.

The effect of thermophoresis is usually prescribed by means of an average velocity acquired by small particles to the gas velocity when exposed to a temperature gradient. In boundary layer flow, the temperature gradient in the  $y$ -direction is very much large than in the  $x$ -direction and therefore only the thermophoretic velocity in  $y$ -direction is considered. As a consequence, the thermophoretic velocity  $V_T$ , which appears in Eq. (5), is expressed in the following form:

$$V_T = -\frac{k_1 v}{T_r} \frac{\partial T}{\partial y} \quad (7)$$

in which  $k_1$  is the thermophoretic coefficient and  $T_r$  is the reference temperature. A thermophoretic parameter  $\tau$  is given by the relation

$$\tau = -\frac{k_1 (T_w - T_\infty)}{T_r} \quad (8)$$

The associated physical boundary conditions are given by

$$u = u_w = ax, v = 0, N = -n \frac{\partial u}{\partial y}, T = T_w, C = C_w \text{ as } y = 0$$

$$u \rightarrow 0, N \rightarrow 0, T \rightarrow T_\infty, C \rightarrow C_\infty \text{ as } y \rightarrow \infty \quad (9)$$

Furthermore, the wall temperature and concentration fields are taken in the following form:

$$T_w = T_\infty + bx, \quad C_w = C_\infty + cx \quad (10)$$

Where  $a, b$  and  $c$  are the positive constants.

Following Sharidan *et al.* [27], we introduce the following non-dimensional variables:

$$\begin{aligned} \psi &= (av)^{\frac{1}{2}} \xi^{\frac{1}{2}} x f'(\xi, \eta), \eta = \left(\frac{a}{v}\right)^{\frac{1}{2}} \xi^{-\frac{1}{2}} y, N = \left(\frac{a}{v}\right)^{\frac{1}{2}} \xi^{-\frac{1}{2}} axh(\xi, \eta), \\ \xi &= 1 - e^{-\zeta}, \zeta = at, \theta(\xi, \eta) = \frac{(T - T_\infty)}{(T_w - T_\infty)}, \phi(\xi, \eta) = \frac{(C - C_\infty)}{(C_w - C_\infty)} \end{aligned} \quad (11)$$

Where  $0 \leq \xi \leq 1$  and  $\Psi$  is the stream function which is defined in the usual form as

$$u = \frac{\partial \psi}{\partial y}, \quad v = -\frac{\partial \psi}{\partial x} \quad (12)$$

So the continuity equation is automatically satisfied. The nonlinear equations and boundary conditions are reduced to

$$\begin{aligned} (1+K)f''' + \frac{\eta}{2}(1-\xi)f'' + Kh' + \xi \\ (ff'' - f'^2 - Mf' + Gr\theta + Gc\phi) = \xi(1-\xi) \frac{\partial f'}{\partial \xi} \end{aligned} \quad (13)$$

$$\begin{aligned} (1+K/2)h'' + \frac{1}{2}(1-\xi)(h + \eta h') + \xi \\ (fh' - f'h - K(2h + f'')) = \xi(1-\xi) \frac{\partial h}{\partial \xi} \end{aligned} \quad (14)$$

$$\frac{1}{Pr}\theta'' + \frac{1}{2}\eta(1-\xi)\theta' + \xi(f\theta' - f'\theta) + D_f\phi'' = \xi(1-\xi) \frac{\partial \theta}{\partial \xi} \quad (15)$$

$$\begin{aligned} \frac{1}{Sc}\phi'' + \frac{1}{2}\eta(1-\xi)\phi' + \xi(f\phi' - f'\phi) \\ -\tau(\theta'\phi' + \theta''\phi) + S_r\theta'' = \xi(1-\xi) \frac{\partial \phi}{\partial \xi} \end{aligned} \quad (16)$$

Where  $M = B_0 \sqrt{\sigma / \rho a}$  is the magnetic parameter,

$Gr = \left[ g\beta(T_w - T_\infty)x^3 / v^2 \right] / (u_w^2 x^2 / v^2)$  is the local

Grashof number,  $Gc = \left[ g\beta(C_w - C_\infty)x^3 / v^2 \right] / (u_w^2 x^2 / v^2)$

is the concentration Grashof number,

$D_f = D\kappa_T(C_w - C_\infty) / c_s c_p v(T_w - T_\infty)$  is the Dufour

number,  $Pr = \mu c_p / k$  is the Prandtl number,

$S_r = D\kappa_T(T_w - T_\infty) / vT_m(C_w - C_\infty)$  is the Soret number,

$Sc = \nu / D$  is Schmidt number. The transformed boundary conditions are

$$\begin{aligned} f(\xi, 0) = 0, f'(\xi, 0) = 1, h(\xi, 0) = \\ -nf''(\xi, 0), \theta(\xi, 0) = 1, \phi(\xi, 0) = 1, \\ f'(\xi, \eta) \rightarrow 0, h(\xi, \eta) \rightarrow 0, \\ \theta(\xi, \eta) \rightarrow 0, \phi(\xi, \eta) \rightarrow 0 \text{ as } \eta \rightarrow \infty \end{aligned} \quad (17)$$

The quantities of physical interest are the local skin-friction coefficient in the  $x$ -direction  $C_{fx}$ , the local Nusselt number  $Nu_x$  and the local Sherwood number  $Sh_x$  are defined respectively by,

$$C_f = \frac{\tau_w}{\rho u_w^2}, \tau_w = \left[ \left( \mu + k_1^* \right) \frac{\partial u}{\partial y} + k_1^* N \right]_{y=0}$$

$$\text{then } C_{fx} Re_x^{\frac{1}{2}} = \xi^{-1/2} \left[ 1 + (1-n)K \right] f''(\xi, 0),$$

$$q_w = -\kappa \left( \frac{\partial T}{\partial y} \right)_{y=0}, Nu_x = \frac{q_w}{(T_w - T_\infty)} \left( \frac{x}{\kappa} \right)$$

$$\text{then } Nu_x Re_x^{\frac{1}{2}} = -\xi^{-\frac{1}{2}} \theta'(\xi, 0),$$

$$m_w = -\rho D \left( \frac{\partial C}{\partial y} \right)_{y=0}, Sh_x = \frac{m_w}{(C_w - C_\infty)} \left( \frac{x}{\rho D} \right)$$

$$\text{then } Sh_x Re_x^{\frac{1}{2}} = -\xi^{-\frac{1}{2}} \phi'(\xi, 0)$$

Where  $Re_x = u_w x / \nu$  is the local Reynolds number based on the surface velocity.

## RESULTS AND DISCUSSION

Equations (13) to (16) with the boundary conditions (17) have been solved numerically using an implicit finite difference scheme, known as the Keller-box. This method has been found to be very suitable in dealing with nonlinear parabolic problems. Details of this method can be seen in the book by Cebeci and Bradshaw [28]. The correctness of the current numerical method is checked with the results obtained by Grubka and Bobba [29] and Ali [30] for the local Nusselt number under the limiting cases. Thus it is seen from Table 1 that the numerical results are in close agreement with those published previously.

Figures 1-4 present the velocity profiles, angular velocity profiles, temperature profiles and concentration profiles for different values of  $\xi$ , for both weak concentration ( $n=1/2$ ) and strong concentration ( $n=0$ ) respectively. These results show that the velocity profiles decrease with increasing  $\xi$ , while the reverse trend is seen on temperature and concentration profiles. It is interesting to note that angular velocity profiles decreases near the stretching sheet whereas reverse effect is observed away from the sheet for weak concentration, while the angular velocity increases for strong concentration with increasing  $\xi$ . Further, from figure 2, it is seen that the angular velocity profile for strong concentrations  $n=0$  is different as compared to weak concentrations  $n=1/2$ . Corresponding to  $n=0$ , it has a parabolic distribution,

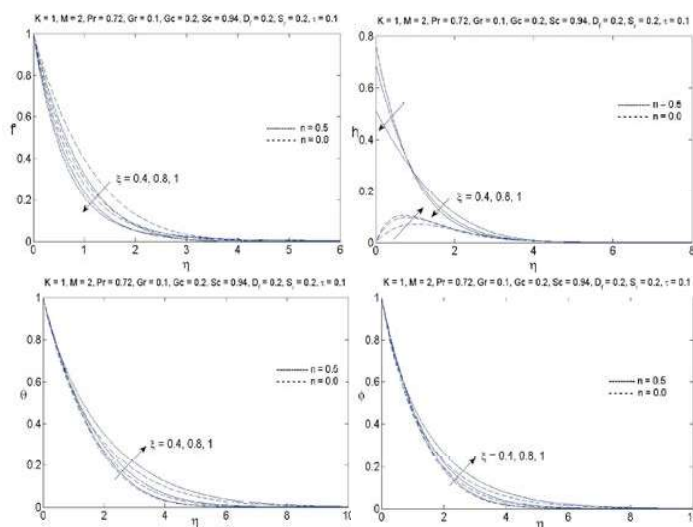
whereas for  $n=1/2$ , it is continuously decreasing. It is evident from this figure that, there is a smooth transition from small time solution ( $\xi=0$ ) to large time solution ( $\xi \approx 1$ ).

The effect of thermophoretic parameter  $\tau$  on concentration fields is shown in Fig. 5. As  $\tau$  increases, the concentration profile decreases.

Figures 6-7 show the effect of the Soret number  $S_r$  on the skin friction, the Nusselt number and the Sherwood number, respectively. As shown, the skin friction and the Nusselt number increase with an increasing the Soret number  $S_r$ , while reverse trend is seen on the Sherwood number. It is also note that the skin friction, the Nusselt number and the Sherwood number increase with an increasing Grashof number.

The effect of Dufour number  $D_f$  on the Nusselt number and the Sherwood number against  $Gr$  are presented in Fig. 8. These results show that the Nusselt number decreases with an increasing Dufour number  $D_f$ , while the Sherwood number increases. It is also noted that the Nusselt number and the Sherwood number increase with an increasing Grashof number  $Gr$ .

Figures 9-10 show the effect of the thermophoresis  $\tau$  on the skin friction, the Nusselt number and the Sherwood number, respectively. These results show that the skin friction and the Nusselt number decrease with an increasing the thermophoresis  $\tau$ , while reverse trend is seen on the Sherwood number.



Figs. 1-4 Effect of unsteady parameter on the velocity, angular velocity, temperature and concentration profiles.

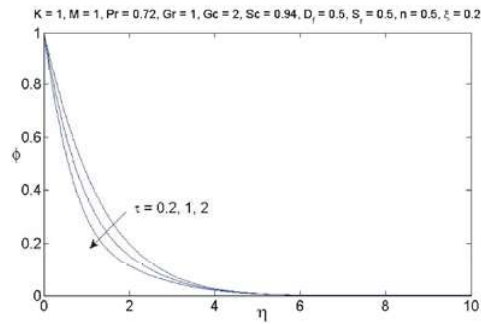
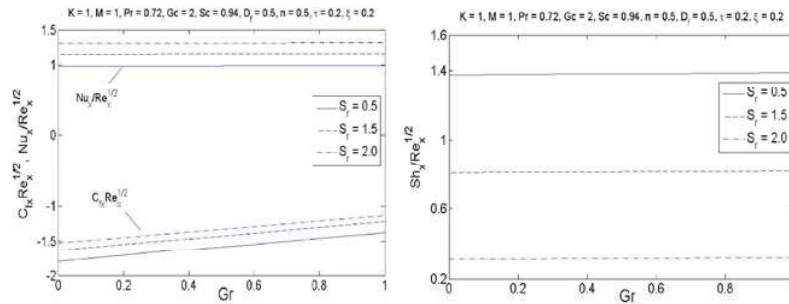


Fig. 5: Concentration profiles for different values of  $\tau$ .



Figs. 6-7: Effect of Soret number on the skin friction, the Nusselt number and the Sherwood number.

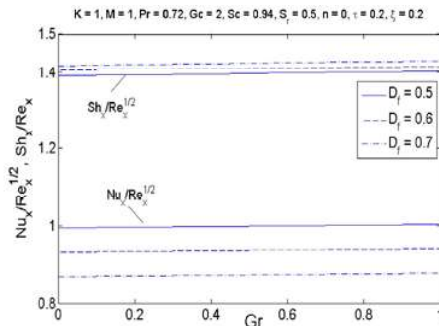
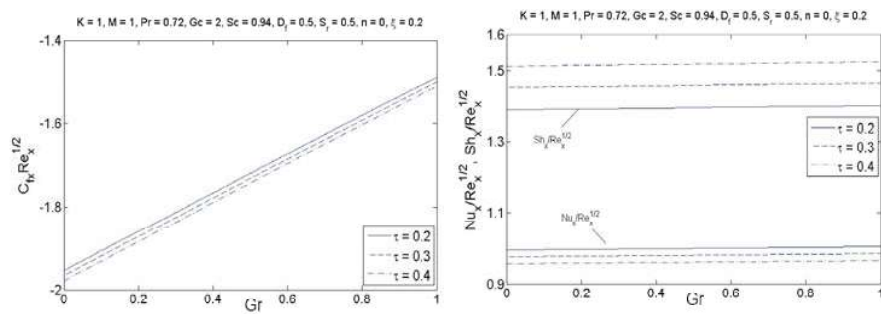
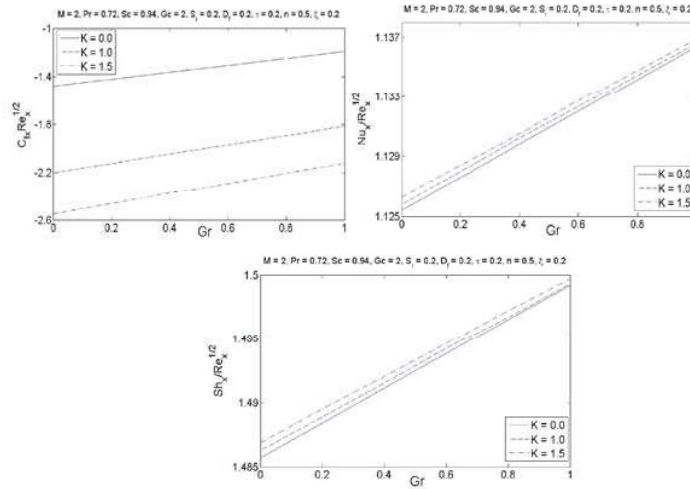


Fig. 8: Nusselt number and the Sherwood number versus  $Dr$  for different values of  $D_f$ .



Figs. 9-10 Effect of thermophoretic parameter on the skin friction, the Nusselt number and the Sherwood number.



Figs. 11-13: Effect of material parameter on the skin friction, the Nusselt number and the Sherwood number.

Table 1: Comparison of values of the local Nusselt number of final steady-state flow ( $\xi=1$ ) for various values  $Pr$  when  $K = Gr = M = Sc = D_f S_r = \tau = 0$ .

$Pr$	Grubka and Bobba [29]	Ali [30]	Present
0.01	0.0197	-	0.0197
0.72	0.8086	0.8058	0.8086
1	1.0000	0.9961	1.0000
3	1.9237	1.9144	1.9237
10	3.7207	3.7006	3.7207

Table 2: Computed of values of skin friction, the local Nusselt number and Sherwood number for various values  $Gr$  and  $K$  when  $Gr=2$ ,  $M=2$ ,  $Sc=0.94$ ,  $Pr=0.72$ ,  $\xi=0.2$ ,  $D_f=0.2$ ,  $S_r=0.2$ ,  $\tau=0.2$ ,  $n=0.5$ .

$Gr$	$K$	$C_{fx} Re_x^{1/2}$	$Nu_x Re_x^{-1/2}$	$Sh_x Re_x^{-1/2}$
0.2	0	-1.4221	1.1276	1.4884
	1.5	-2.4615	1.1284	1.4895
0.6	0	-1.3067	1.1320	1.4938
	1.5	-2.2899	1.1327	1.4946
1.0	0	-1.1916	1.1364	1.4992
	1.5	-2.1190	1.1369	1.4997

The effect of material parameter on the skin friction, the Nusselt number and the Sherwood number is against  $Gr$  are depicted in Figs. 11-13. From figure 11, it is observed that the skin friction decreases with an increasing material parameter, while the reverse trend is observed on the Nusselt number and the Sherwood number.

Finally, the values of the skin friction, the Nusselt number and the Sherwood number are tabulated in Table 2 for various values of  $Gr$  and  $K$ . It is noted from this table that the Nusselt number and the Sherwood number increase with an increase in the value of  $K$ , while the skin friction decreases.

## CONCLUSION

In this work, free convection heat and mass transfer over an unsteady stretching surface in a micropolar fluid in the presence of thermophoresis and Soret and Dufour effects has been investigated. The numerical results obtained and compared with previous published results and were found in good agreements. In the light of present investigation, we found that due to the  $\xi$ , the velocity profiles decreases, while reverse trend is seen on the temperature and concentration profiles. The angular velocity decreases near the stretching sheet, whereas the reverse effect is observed away from the sheet for weak concentrations, whereas the angular velocity increases for strong concentrations. In addition, the skin friction and the Nusselt number increase with an increasing Soret number  $S_r$ , while the Sherwood number decreases. Further, thermophoresis parameter decreases the skin friction and the Nusselt number, while the reverse trend is seen on the Sherwood number. Moreover, the Nusselt number decreases with an increasing Dufour parameter, while the Sherwood number decreases. Furthermore, the skin friction decreases due to increase in the material parameter, while the Nusselt number and the Sherwood number increase.

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